Compensating for Environmental Variability in the Thermal Inertia Approach to Remote Sensing of Soil Moisture[1]

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ABSTRACT

A procedure is developed for removing data scatter in the thermal inertia approach to remote sensing of soil moisture that arises from environmental variability in time and space. It entails the utilization of nearby National Weather Service air temperature measurements to normalize measured diurnal surface temperature variations to what they would have been for a day of standard diurnal air temperature variation, arbitrarily assigned to be 18°C. Tests of the procedure's basic premise on a bare loam soil and a crop of alfalfa indicate it to be conceptually sound. It is possible the technique could also be useful in other thermal inertia applications, such as lithographic mapping.

1. Introduction

A major goal of several scientific groups in the United States is to develop a practical procedure for estimating water content near the surfaces of bare soils and throughout the root zones of crops from data that can be gathered remotely. Such a feat, if accomplished, would open the door to a host of economically important activities, such as predicting world harvests, crop pest outbreaks, plant disease epidemics, fertilizer requirements, irrigation needs, etc. (Idso *et al.*, 1975a). Two basic approaches to achieving this goal that have shown substantial indications of success are to relate soil water contents to 1) the magnitudes of the differences between daily maximum and minimum soil or crop canopy temperatures, and 2) the differences between maximum soil or crop canopy temperature and concurrent air temperature (Idso *et al.*, 1975b; Idso and Ehrler, 1976).

The first of these procedures is what has been known historically as the "thermal inertia" approach. It has also been used in determining the nature of lunar surface materials prior to spacecraft landings (Wesselink, 1948; Jaeger, 1953; Sinton, 1962) and in the lithographic mapping of portions of the earth's surface (Watson, 1973, 1975; Watson *et al.*, 1971; Pohn *et al.*, 1974; Kahle *et al.*, 1976).

A problem equally bothersome to both of these applications is environmental variability—the nonuniformity from day-to-day or from season-to-season or from place-to-place of the external forcing functions of the daily surface temperature wave which are not related to the surface information being sought. In this paper we present a solution to this problem that may considerably expand the potentials for both remote sensing of soil moisture and lithographic mapping.

2. Theory

The amplitude of the diurnal surface temperature wave of any substrate material, be it soil, rock or plant canopy, is a function of both internal and external factors. The internal factors are thermal conductivity (λ), density (ρ) and specific heat (c), where

$$P = (\lambda\rho c)^{\frac{1}{2}} \tag{1}$$

defines what is known as "thermal inertia." The external factors include such items as solar radiation, air temperature, atmospheric precipitable water content, cloudiness, wind, aerosol concentration, etc. These factors generally are not treated individually in the mathematical formalism of thermal inertia analyses, however, but their myriad combinations are instead expressed by a single resultant forcing function, i.e., the surface heat flux.

The specific relationship between the thermal inertia and surface heat flux derives from consideration of the equation for one-dimensional heat flow in a semi-infinite solid, i.e.,

$$\frac{\partial T}{\partial t} = \frac{\lambda}{\rho c}\frac{\partial^2 T}{\partial z^2}. \tag{2}$$

For a sinusoidally varying surface heat flux of amplitude G, the variation of surface temperature (T_s) about some

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mean value is thus given by

$$(T_s - T_{s,\,\mathrm{av}}) = \frac{G\sin(\omega t - \frac{1}{4}\pi)}{(\omega\rho c\lambda)^{\frac{1}{2}}}, \qquad (3)$$

from which the amplitude of the surface temperature variation is found to be

$$0.5\Delta T_s = \frac{G}{P\omega^{\frac{1}{2}}}, \qquad (4)$$

where $\Delta T_s = T_{s,\,\max} - T_{s,\,\min}$.

Thus, the thermal inertia of a given substrate is seen to be inversely proportional to the amplitude of its diurnal surface temperature oscillation. However, as environmental conditions vary over the earth and in time, G may vary considerably, which in turn causes the amplitude of the surface temperature wave ($0.5\Delta T_s$) to vary. This variation is not due to variations in P and therefore creates problems for both lithographic mapping (based on P discrimination from ΔT_s measurements) and soil water content θ_v estimation (based on θ_v vs ΔT_s relations that arise from the variation of λ with θ_v).

As a first step in compensating for environmental variability, we propose to normalize ΔT_s measurements to what they would have been for some arbitrary standard value of surface heat flux (G_{std}). That is, we transform *actual* ΔT_s data into *normalized* ΔT_s data ($\Delta T_{s,\,\mathrm{nor}}$) via the relationship

$$\frac{\Delta T_s}{\Delta T_{s,\,\mathrm{nor}}} = \frac{G}{G_{\mathrm{std}}}. \qquad (5)$$

Thus, in any situation, where ΔT_s is measured and G is known, we can transform ΔT_s into $\Delta T_{s,\,\mathrm{nor}}$, allowing us to make use of a standard $\Delta T_{s,\,\mathrm{nor}}$ vs P or θ_v relation that is reasonably independent of environmental conditions.

A problem with this approach is that G is usually not known. Thus, a surrogate for it must be found. Air temperature (T_A) would appear to be the ideal candidate for two reasons. First, it is one of the most commonly measured meteorological parameters on earth. Second, air temperature responds in very similar fashion to the effects of environmental factors that affect surface temperature. Indeed, it does so because its diurnal variation is driven by convective coupling with the surface. Thus, we postulate that

$$\frac{\Delta T_s}{\Delta T_{s,\,\mathrm{nor}}} = \frac{G}{G_{\mathrm{std}}} = \frac{\Delta T_A}{\Delta T_{A,\,\mathrm{std}}}, \qquad (6)$$

and propose that all ΔT_s data be normalized with

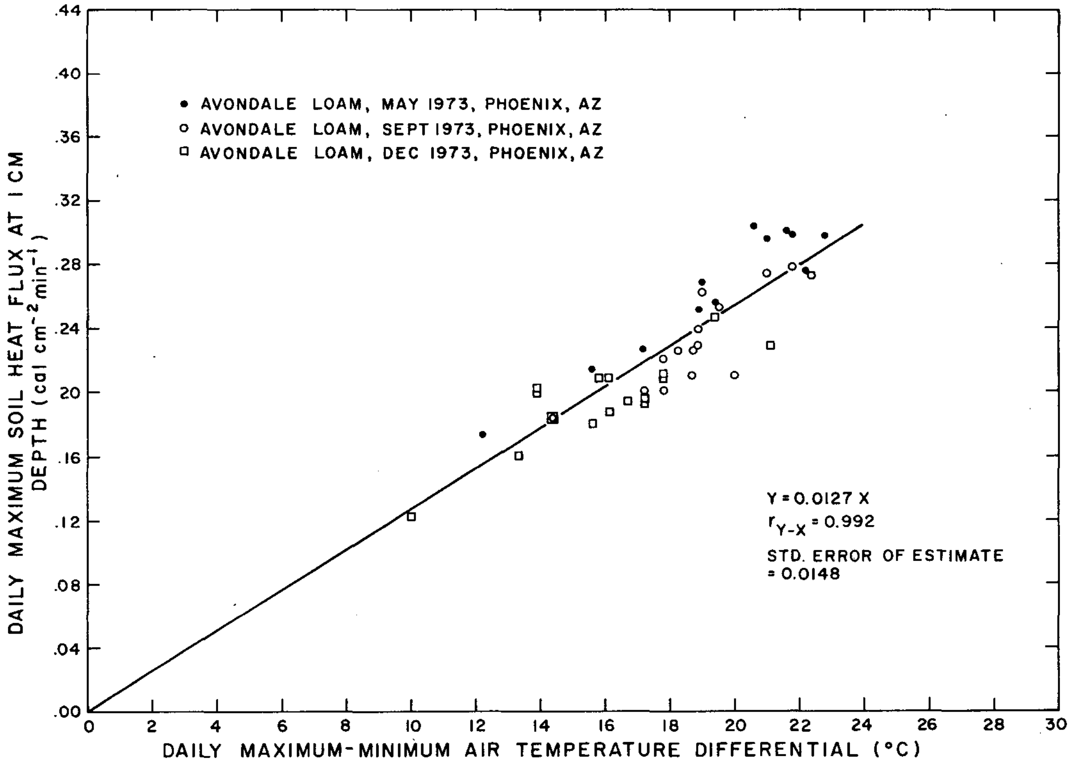

FIG. 1. The daily maximum soil heat flux at 1 cm depth in a smooth bare field of Avondale loam at Phoenix, Ariz., versus the daily maximum-minimum air temperature differential measured at the Phoenix National Weather Service Station.

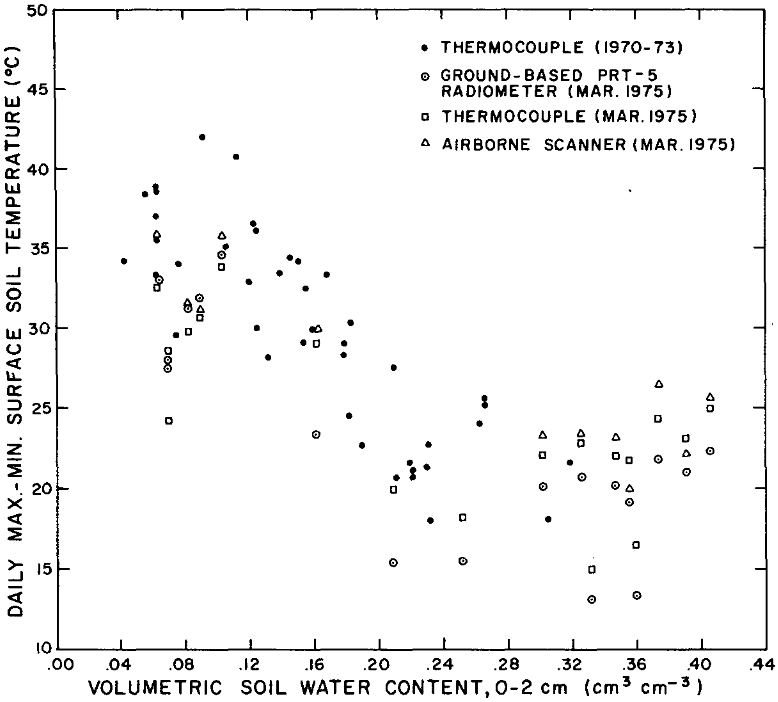

Fig. 2. The maximum-minimum surface temperature differential of a smooth bare field of Avondale loam versus the average daily volumetric soil water content of the uppermost 2 cm.

respect to an arbitrary standard diurnal air temperature variation.

3. Test of the heat flux-air temperature relationship

During three of our extensive experiments on θ_v vs ΔT_s relationships in a smooth bare field of Avondale loam (Idso *et al.*, 1975b), we also obtained measurements of soil heat flux at a depth of 1 cm. These measurements were made with National Instruments Laboratory[2] Model HF-1 heat flow discs calibrated by the procedure of Idso (1972). Since our analysis of the T_s data indicated that the variations in ΔT_s as θ_v changed were due primarily to changes in $T_{s,\max}$ and since $G_{\min}$ also appeared to be quite invariant and small, we plotted daily $G_{\max}$ vs ΔT_A as shown in Fig. 1, where the T_A data were obtained from the nearby Phoenix National Weather Service Station. The results clearly indicate that there is indeed a linear relation between $G_{\max}$ and ΔT_A of such a nature as to justify Eq. (6).

4. Test of the normalization procedure applied to bare soil

Fig. 2 contains the original ΔT_s vs θ_v data of Idso *et al.* (1975b) plus some more recent data obtained by Reginato *et al.* (1976) on the same Avondale loam soil at Phoenix. For each of the days represented by data points in Fig. 2, we obtained the maximum and minimum air temperatures recorded by the Phoenix National Weather Service Station and utilized Eq. (6) to transform the ΔT_s values into $\Delta T_{s,\text{nor}}$ values by arbitrarily assigning $\Delta T_{A,\text{std}}$ a value of 18°C. With this operation the data of Fig. 2 were transformed into the data of Fig. 3, where the scatter among the data points is seen to be significantly reduced.

The choice of 18°C for $\Delta T_{A,\text{std}}$ is completely arbitrary. Any number could have been chosen. However, to make data from different locations and seasons compatible, once a number has been chosen, it must be used exclusively.

5. Test of the normalization procedure applied to a crop

Four separately irrigated 1 ha plots of Avondale loam planted to alfalfa at Phoenix were studied from 16 June to 23 July, 1975. Every Monday, Wednesday and Friday canopy surface temperatures were measured just before sunrise and about an hour and a half past solar noon. On Tuesdays and Thursdays only the afternoon measurements were made. The canopy temperatures were measured with a 20° field-of-view Barnes PRT-5 infrared thermometer,[2] hand-held at about a 45° angle with the ground approximately 1 m above the crop surface. Preliminary tests using a utility platform that could be raised 9 m high indicated that once

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[2] Trade names or company names are included for the benefit of the reader and imply no endorsement or preferential treatment of the product listed by the U. S. Department of Agriculture.

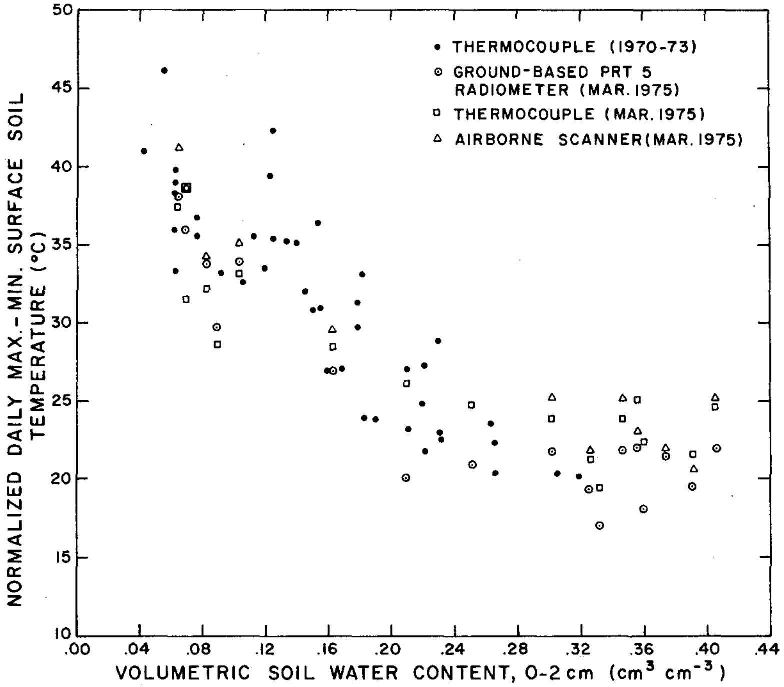

FIG. 3. The normalized (as described in the text) maximum-minimum surface temperature differential of a smooth bare field of Avondale loam versus the average daily volumetric soil water content of the uppermost 2 cm.

the alfalfa was 30 cm high, canopy temperatures did not vary when they were obtained at viewing angles ranging from 0° to 50° from perpendicular over the height range 1–9 m.

At the same times that canopy temperatures were measured, air temperatures were measured 1 m above the crop canopy by means of an aspirated psychrometer. Every Monday, Wednesday and Friday we also sampled gravimetric soil water content in each of the four fields at 30 cm increments to a depth of about 2 m.

The first analyses we made with these data were to test the two basic procedures for estimating root-zone soil water contents. Thus, in Figs. 4 and 5 we plotted the 1400 local time canopy-air temperature differential versus the volumetric water content of the 0 to 2 m root zone, and the 1400–0500 canopy temperature differential versus the same parameter. Volumetric water contents were obtained by multiplying the measured gravimetric values by the soil's mean bulk density.

The lines drawn on Fig. 4 depict a relation developed by Idso and Ehrler (1976) for cotton and sorghum grown on the same soil type. Our present results for alfalfa show essentially the same pattern. Data for non-water-stressed plants essentially fill up the "bathtub" part of the graph, where there is no unique relation between θ_v and the canopy-air temperature differential. The alfalfa we studied was always irrigated at the proper intervals and never really stressed to push the data onto the predictive portion of the graph defined by the single line for $\theta_v \leqslant 0.19$.

With this thought in mind let us consider the data of Fig. 5. At first glance they appear to be devoid of much meaning. However, it is noticed that they fall into two major groups: "pre-monsoon" and "during monsoon." Since our data were all gathered at one location and we could not traverse great latitude changes to experience different air temperature regimes due to solar altitude variations, we conducted our experiment over the period of abrupt climatic change that occurs with the arrival of Arizona's summer monsoon. During June, Arizona normally experiences very dry weather. However, in early July it becomes immersed in moist air from both the Gulf of Mexico at high levels, and the Gulf of California at low levels. The low-level source has recently been documented to be the primary source (Hales, 1974), which causes the atmospheric precipitable water content to about triple in very abrupt fashion. The effect of this change in atmospheric humidity is to greatly reduce the amplitude of the diurnal air temperature wave, as shown in Fig. 6. Thus, data obtained before and after the monsoon's arrival present an ideal opportunity for testing our normalization procedure.

Then operating on the data of Fig. 5, in analogous fashion to our normalization of the bare soil data that transformed Fig. 2 into Fig. 3 [that is, using Eq. (6) with $\Delta T_{A,\,\mathrm{std}} = 18°\mathrm{C}$], we now find Fig. 5 transformed

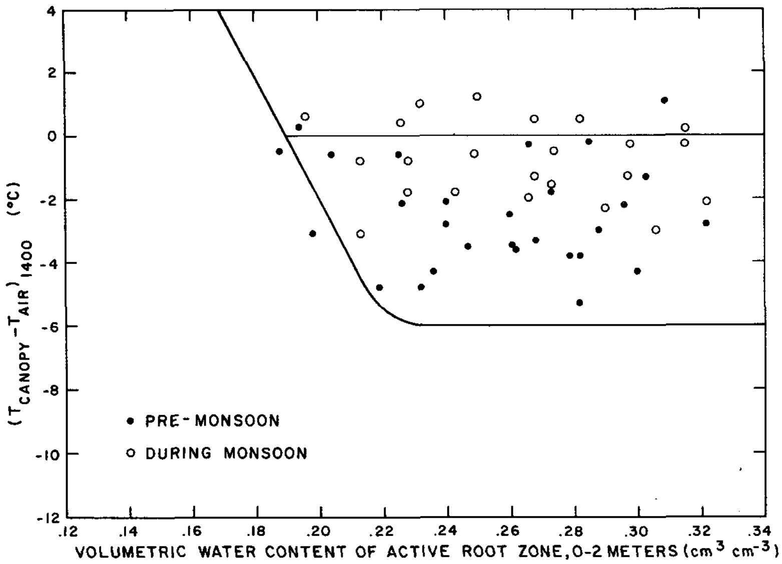

FIG. 4. Maximum canopy-air temperature (obtained 1 m above the crop) differential of four different fields of mature alfalfa as obtained from measurements made at 1400 local time versus the volumetric water content of the crops' active root zone.

into Fig. 7. The reduction of data scatter in this instance is even more than for the bare soil case. Indeed, the scatter is cut to only about a third of what it was prior to normalization.

The maximum surface-air temperature differential approach cannot claim this same advantage, however, since correct *absolute* values are required for both the surface and air temperatures in order to get a valid differential value. To illustrate, if Phoenix National Weather Service air temperatures are used instead of air temperatures measured just above the crop, the plot of Fig. 4 changes to that of Fig. 8. Considerably more

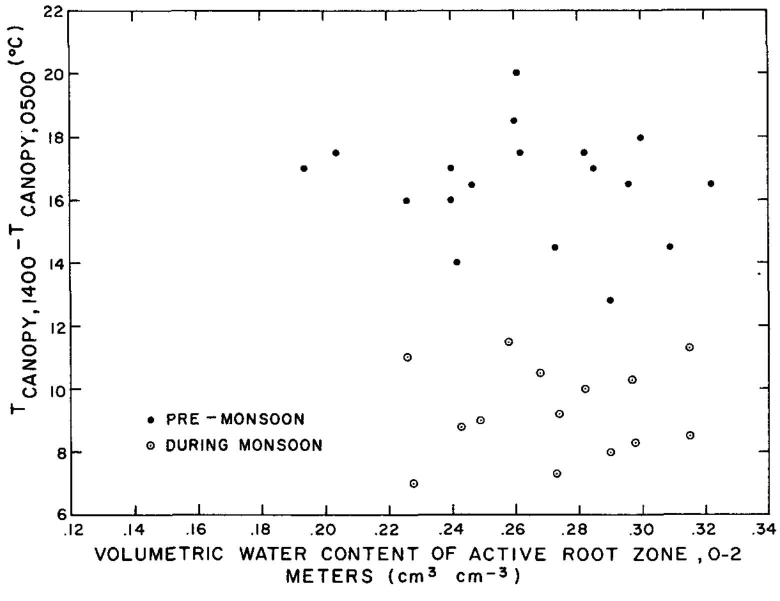

FIG. 5. The maximum-minimum canopy temperature differential of four different fields of mature alfalfa as obtained from measurements made at 1400 and 0500 local time versus the volumetric water content of the crops' active root zone.

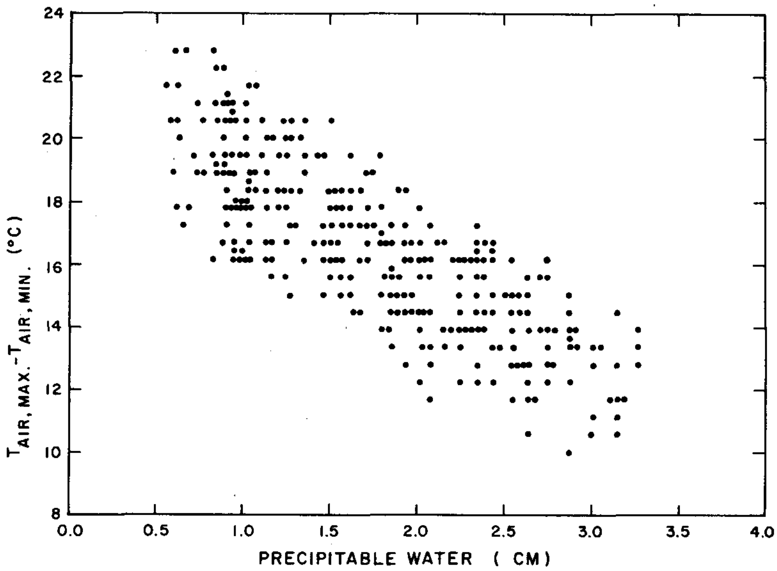

FIG. 6. The maximum-minimum air temperature differential obtained from official National Weather Service records for Phoenix as a function of the mean daily atmospheric precipitable water content obtained from National Weather Service dew point data and a procedure outlined by Idso (1969).

scatter is inherent in the data of Fig. 8, and the predetermined soil water content relationship is significantly violated.

6. Concluding discussion

In normalizing both the bare soil surface temperature data and the alfalfa canopy temperature data, we utilized maximum and minimum air temperatures measured at the Phoenix National Weather Service Station. Although one cannot expect absolute magnitudes of maximum and minimum air temperatures to be the same over a transpiring crop or moist soil surface and an asphalt-surrounded airport site several kilometers away, the maximum-minimum air temperature *differentials* apparently may be quite similar. This fact greatly increases the potential for using the standard thermal inertia approach in remote sensing of soil moisture, since no *in situ* measurements need to be

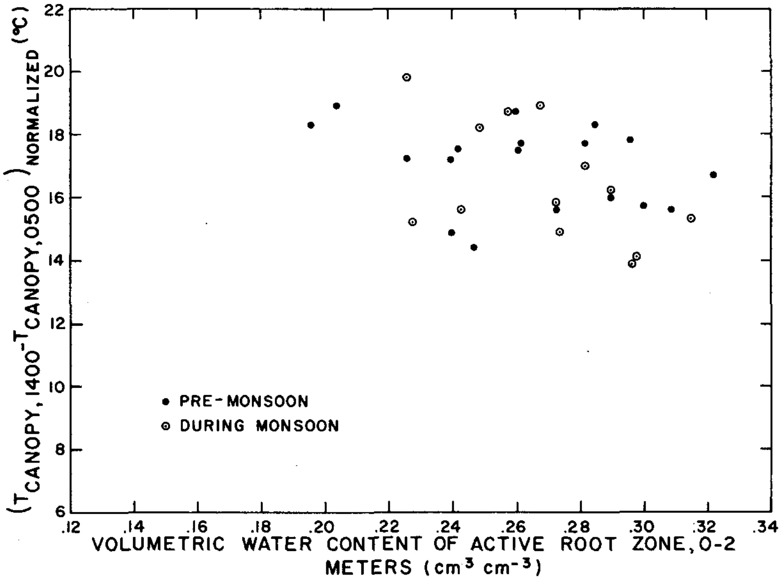

FIG. 7. The normalized (as described in the text) maximum-minimum canopy temperature differential of four different fields of mature alfalfa as obtained from measurements made at 1400 and 0500 local time versus the volumetric water content of the crops' active root zone.

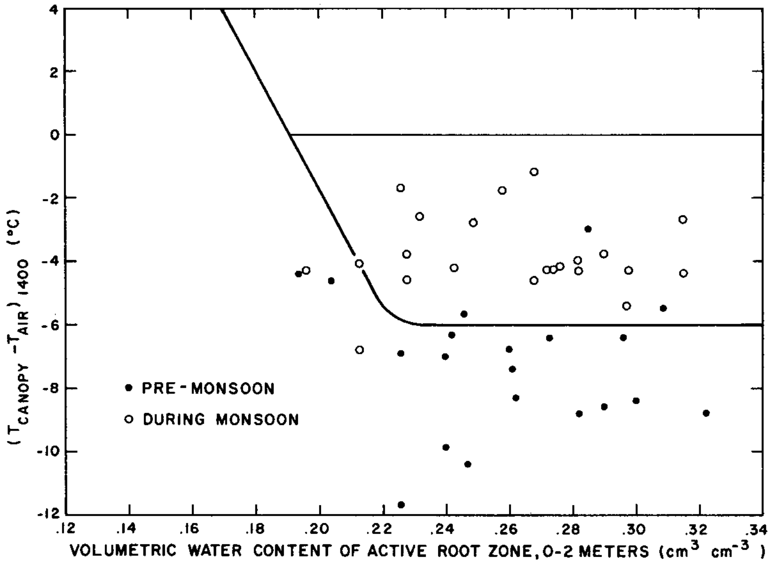

FIG. 8. Maximum canopy-air temperature (obtained from Phoenix National Weather Service Station) differential of four different fields of mature alfalfa as obtained from measurements made at 1400 local time versus the volumetric water content of the crops' active root zone.

made. It is also possible the technique may be of some usefulness in certain lithographic mapping applications, in areas where the required air temperatures are available.

Certain limitations to the technique still remain, however, and should be pointed out. First of all, the improved bare soil relationship depicted in Fig. 3 is applicable to only shallow depths on the order of a few centimeters, specifically 2 cm in this particular plot. Also, the $\Delta T_{s,\,\mathrm{nor}}$ vs θ_v relation there depicted is applicable to Avondale loam only. However, Idso *et al.* (1975b) have shown that if the θ_v values are converted to soil water pressure potential or tension values, a more universal relation results that does appear to be independent of soil type.

Finally, it should be reemphasized that the alfalfa data we used do not represent a predictively useful set. A predictive relation was demonstrated by Idso and Ehrler (1976) to exist only for water contents below about 0.19 cm^3 cm^{-3} for this particular soil. Above that value $(T_{\mathrm{canopy}}-T_A)_{1400}$ values and $(T_{\mathrm{canopy},\,1400}-T_{\mathrm{canopy},\,0500})$ values fall in a region constrained only to a range of scatter on the order of 6°C. Thus, this paper does not pretend to elucidate further on the predictive nature of surface temperature and root zone soil water content relationships, but only indicates that the normalization procedure developed can significantly reduce the scatter in this type of data due to environmental variability.

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